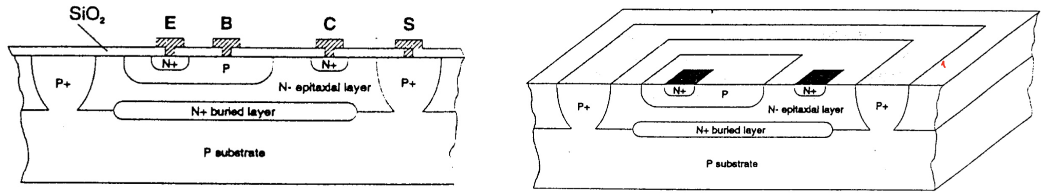
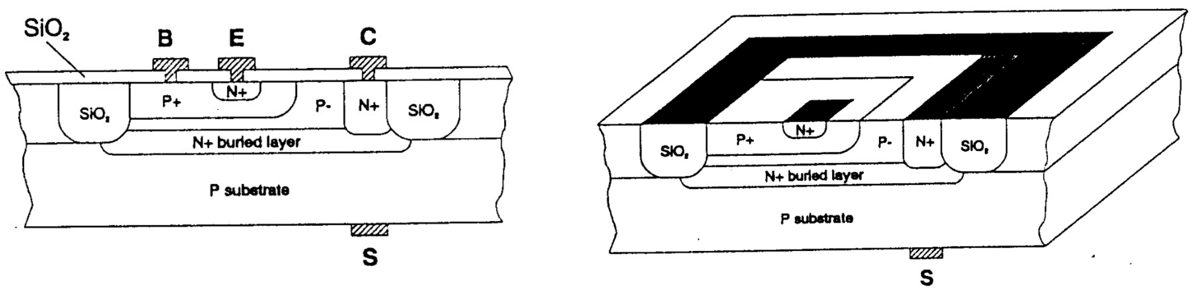
Chapter 3: Bipolar Junction Transistor

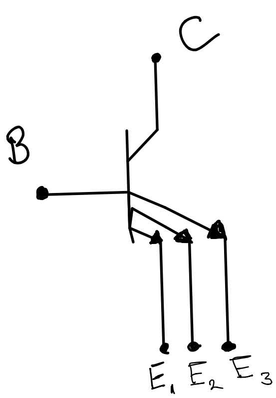
Junction isolated NPN BJT



Oxide isolated NPN BJT



Multi-Emitter BJT



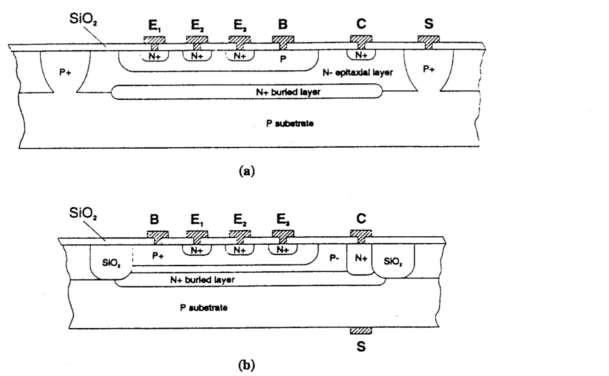
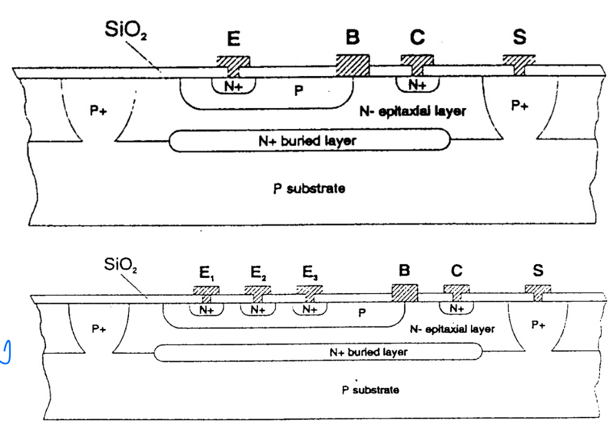


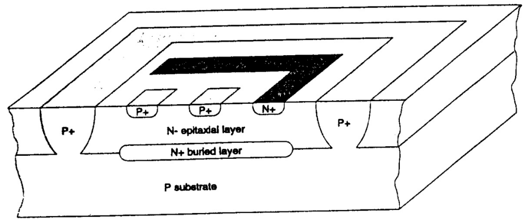
FIGURE 3.3 Multi-emitter NPN BJTs: (a) Junction isolation technology, (b) Oxide isolation technology

Schottky-clamped BJT

* The base contact is extended over the N collector region which forms schottky diode in parallel with the base collector PN junction
* Multi-emitter BJT converted to Schottky clamped BJT's by placing schottky MN diode in parallel with the PN base-collector junction.



Lateral PNP BJT:



* Lateral PNP BJT is construct from PNP BJT's along with NPN BJT's.

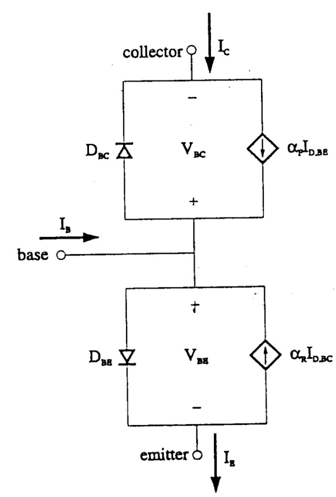
* Lateral PNP have much reduced β_f because the base width is about an order of magnitude larger than that of the NPN.

* β_f for the PNP is reduced due to uniform N base doping as well as reduced emitter carrier collection at the collector as compared with the NPN.

The Ebers-Moll BJT Model

* A simple model that represents the first order DC operation of BJT.

NPN BJT Model



Ebers-Moll NPN BJT Model

$$I_{D,BE} = I_{ES}\left(e^{V_{BE}/\phi_T} - 1\right)$$

$$I_{D,BC}(V_{BC}) = I_{CS}\left(e^{V_{BC}/\phi_T} - 1\right)$$

$I_{ES} \equiv$ Base-emitter saturation current

$I_{CS} \equiv$ Base-collector saturation current.

$$\alpha_F I_{D,BE} = \alpha_F I_{ES}\left(e^{V_{BE}/\phi_T} - 1\right)$$

$$\alpha_R I_{D,BC} = \alpha_R I_{CS}\left(e^{V_{BC}/\phi_T} - 1\right)$$

$\alpha_F \equiv$ common base forward current amplification factor

$\alpha_R \equiv$ common base reverse current amplification factor.

Typically $0 < \alpha_F < 1$

$$0.2 \leq \alpha_R \leq 0.6$$

$$I_E = I_{ES}\left(e^{v_{BE}/\phi_T} - 1\right) - \alpha_R I_{CS}\left(e^{v_{BC}/\phi_T} - 1\right)$$

$$I_C = \alpha_F I_{ES}\left(e^{v_{BE}/\phi_T} - 1\right) - I_{CS}\left(e^{v_{BC}/\phi_T} - 1\right)$$

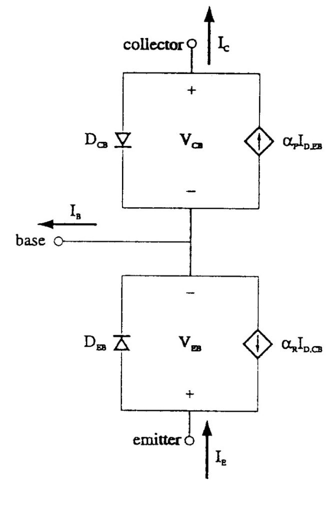
$$I_E = I_B + I_C$$

PNP BJT Model

$$I_E = I_{D,EB} - \alpha_R I_{D,CB}$$
$$= I_{ES}\left(e^{v_{EB}/\phi_T} - 1\right) - \alpha_R I_{CS}\left(e^{v_{CB}/\phi_T} - 1\right)$$

$$I_C = \alpha_F I_{D,EB} - I_{D,CB}$$
$$= \alpha_F I_{ES}\left(e^{v_{EB}/\phi_T} - 1\right) - I_{CS}\left(e^{v_{CB}/\phi_T} - 1\right)$$

$$I_E = I_B + I_C$$



Ebers-Moll PNP BJT Model

Reciprocity theorem

* I_{ES}, I_{CS}, α_F & α_R parameters are related by the reciprocity theorem for the ideal BJT.

$$\alpha_F I_{ES} = \alpha_R I_{CS} = I_S$$

BJT Modes of Operation

BJT Modes of Operation

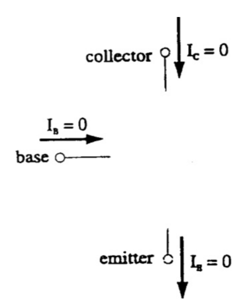
Base-Emitter PN Junction Bias	Base-Collector PN Junction Bias	Mode of Operation
Reverse	Reverse	Cutoff
Forward	Reverse	Forward active
Forward	Forward	Saturation
Reverse	Forward	Reverse active

Cut-off Mode

* Both PN Junctions of the BJT are reverse biased
* ∴ $I_{D,BE}$ & $I_{D,BC}$ are zero. therefore $\alpha_F I_{D,BE} = \alpha_R I_{D,BC} = 0$.

$$I_{E(off)} = 0$$

$$I_C\,(off) = 0$$



* The actual currents are in the nanoamp range.

$$I_B = I_C = I_E \cong 0$$

Forward Active Mode.

$J_{BE} \Rightarrow$ Forward biased

$J_{BC} \Rightarrow$ Reverse biased.

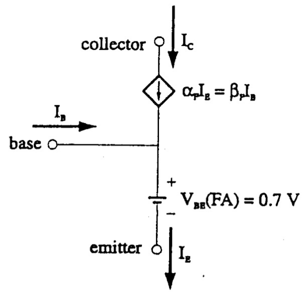
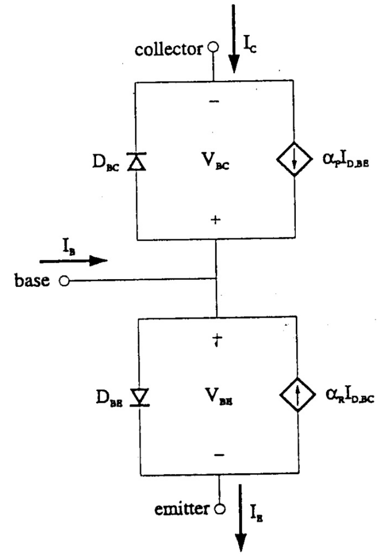


FIGURE 3.9 Reduced NPN BJT Model for the Forward Active Mode of Operation



Ebers-Moll NPN BJT Model

$I_{D,BC} \approx 0$

$V_{BE}(FA) = 0.7V$ (for silicon diodes)

$$I_E = I_B + I_C$$

$$I_C(FA) = \alpha_F I_E$$

$$I_C(FA) = \beta_F I_B$$

$$\beta_F = \frac{\alpha_F}{1 - \alpha_F}$$

Saturation Mode.

* Both J_{BE} & J_{BC} are forward biased.
* In saturation mode I_C, I_E & I_B are larger than in other modes of operation
* Due to larger currents $V_{BE} > [V_{BE}(FA) = 0.7]$

$$V_{BE}(sat) = 0.8 \text{ V}$$

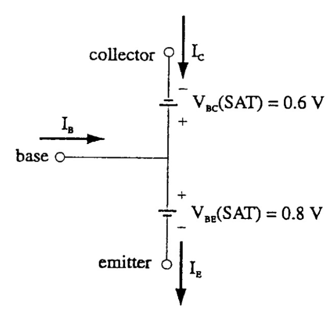


FIGURE 3.10 Reduced NPN BJT Model for the Saturated Mode of Operation

* Due to lighter doping v_{BC} will typically not exceed:

$$v_{BC}(sat) = 0.6V$$

* Due to v_{BE} & v_{BC} values:

$$v_{CE}(sat) = 0.2\,V$$

* A saturation parameter σ indicates the relationship between I_C & I_B and its defined as

$$\sigma = \frac{I_C}{\beta_F I_B}, \quad \sigma \leq 1$$

* $\sigma = 1$ means FA operation and/or edge of saturation operation

Reverse Active Mode

JBE is reverse biased

JBC is forward biased

$$V_{BC}(RA) = 0.7V$$

$$I_E(RA) = \alpha_R I_C = -\beta_R I_B < 0$$

$$\beta_R \ll \beta_F$$

$$\beta_R = \frac{\alpha_R}{1-\alpha_R}$$

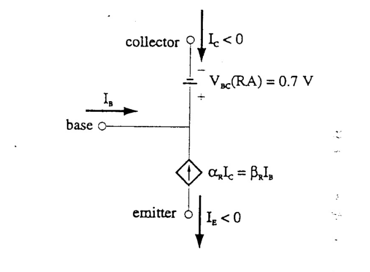
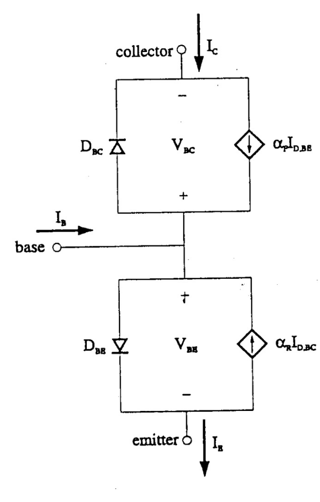


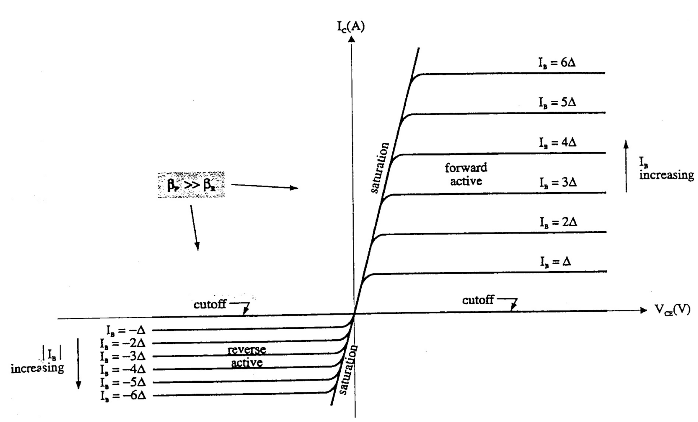
FIGURE 3.11 Reduced NPN BJT Model for the Reverse Active Mode of Operation



Ebers-Moll NPN BJT Model

Family of Curves

* For equal increments in I_B the curves in the active regions are approximately evenly spaced.
* Curves in RA region are much closer together than those in FA region
* Ebers-Moll predicts that β_F & β_R are independent of the terminal current magnitudes but this is not entirely true.



The Gummel-Poon BJT Model

* This model considers several second-order effects some of these are:
  - The early effect (base-width modulation)
  - The Sah-Noyce-Shockley effect
  - The Kirk effect (base width widening)

The Early Effect (Base-Width Modulation)

* I_C vs V_{CE} curves obtained from the ebers-moll model shows no dependence of I_C on V_{CE} but there is a dependence observed due to early effect and its obvious on gummel-poon model curves.
* The slopes of I_C vs V_{CE} increase as I_B increases
* When the linear portion of the curves are extrapolated on the negative V_{CE} axis they intersect at a common voltage $-V_A$
* $V_A \equiv$ Early voltage
* The early effect is also present in the reverse active mode.

$$I_C = I_S\left(e^{v_{BE}/\phi_T} - e^{v_{BC}/\phi_T}\right)\left(1 - \frac{V_{BC}}{V_A}\right) - \frac{I_S}{\beta_R}\left(e^{v_{BC}/\phi_T} - 1\right)$$

$$I_B = \frac{I_S}{\beta_F}\left(e^{v_{BE}/\phi_T} - 1\right) + \frac{I_S}{\beta_R}\left(e^{v_{BC}/\phi_T} - 1\right)$$

$$I_E = I_B + I_C$$

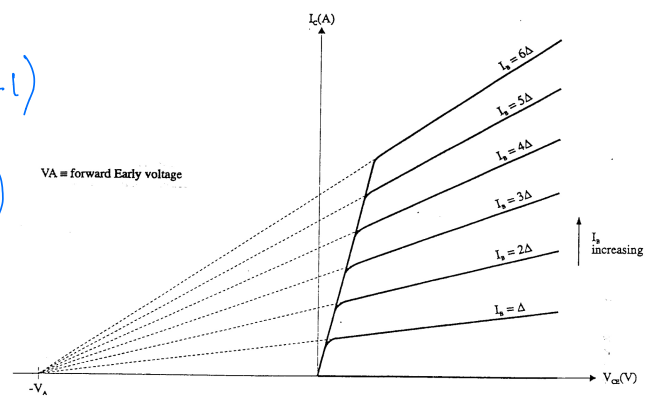


FIGURE 3.13 V_{CE} Dependence on I_C due to the Early Effect

* Electronic devices and integrated circuit 2nd edition by Ajay Kumar Singh
* Semiconductor Device Physics and Design by Umesh K. Mishra & Jasprit Singh

The Kirk Effect (Base Width Widening)

* When the minority carrier concentration across the base-collector junction increases the electron concentration becomes comparable to the doping density of the collector This has the effect of widening the base region & reducing the injected minority carriers that reach the collector and therefore β_F is reduced

Low Current level Depletion Layer Recombination

In BJT the depletion layer recombination increases the base current and therefore decreases the current gain.

$$I_D' = I_S\left(e^{v_D/N\phi_T} - 1\right)$$

SPICE BJT Model

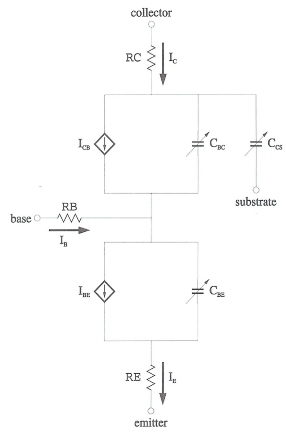


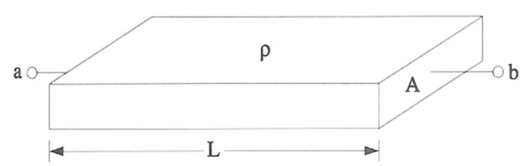
FIGURE 3.14 SPICE BJT Model (Modified Gummel-Poon model)

Integrated circuit resistors

* TTL & ECL families continue to use IC resistors.

Ideal Rectangular Resistor.

$$R_{ab} = \rho \frac{L}{A}$$



where:

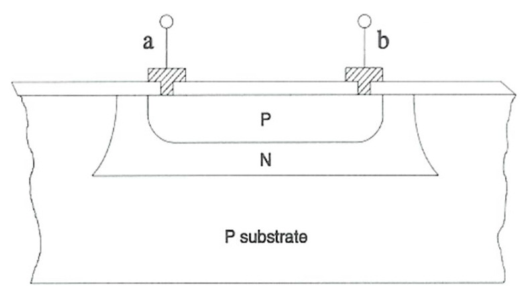
$\rho \equiv$ constant of resistivity

$L \equiv$ Length.

$A \equiv$ cross-section area.

Diffused Base Resistor

* Using the base diffusion/implant region



$$R_{ab} = \rho_{SB} \frac{L}{W}$$

$\rho_{SB} \equiv$ sheet resistivity

* ρ_{SB} of this region is comparatively large and is useful for large IC resistors.

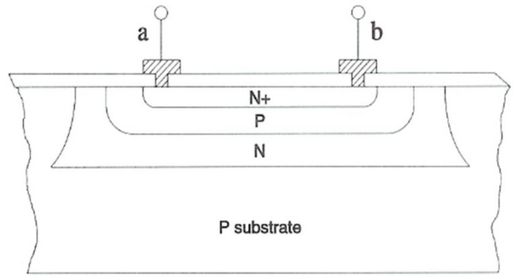
$$\boxed{\rho_{SB} = \frac{\rho}{t}}$$

* Typically $\rho_{SB} = 200\,\Omega/\text{square}$.

$t \equiv$ tickness

Diffused Emitter Resistor

* Using the emitter N^+ region for the resistor

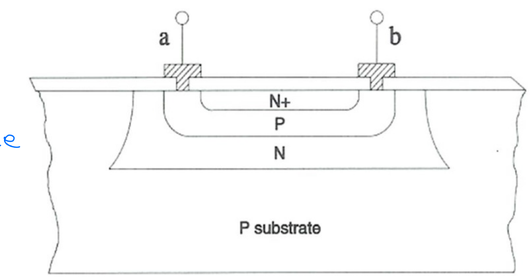


$$R_{ab} = \rho_{SE} \frac{L}{W}$$

* Typically $\rho_{SE} = 2\,\Omega/\text{square}$.
* This resistor used for small valued resistors

Pinch Resistor

* Because the cross section of the pinch resistor has been reduced by N^+ diffusion It has the largest value of resistance for a fixed length/width ratio of any of the IC resistors.



* The reduced cross-section has the effect of increasing the sheet resistivity and hence resistor value.

$$R_{ab} = \rho'_{SB} \frac{L}{W}$$